AFRL-OSR-VA-TR-2013-0025

Design, Integration and Flight Test of a Pair of Autonomous Spacecraft Flying in Formation

Henry Pernicka

Missouri University of Science and Technology

May 2013
Final Report

DISTRIBUTION A: Approved for public release.

AIR FORCE RESEARCH LABORATORY
AF OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
ARLINGTON, VIRGINIA 22203
AIR FORCE MATERIEL COMMAND

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
04-07-2011	Final	01-03-2009 to 31-05-2011

4. TITLE AND SUBTITLE

Design, Integration, and Flight Test of a Pair of Autonomous Spacecraft Flying in Formation

5a. CONTRACT NUMBER

5b. GRANT NUMBER
Grant FA9550-09-1-0171

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Henry J. Pernicka

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Missouri University of Science and Technology
Dept. of Mechanical and Aerospace Engineering
400 West 13th Street
Rolla, MO 65409-0050

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Dr. Kent Miller, Program Manager
AFOSR/NE
875 N. Randolph St., Suite 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2013-0025

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited.

Distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
As participants in AFRL's University Nanosat Program, the Missouri University of Science and Technology successfully produced a nearly flight-ready microsatellite that was presented at the Final Competition Review held in Albuquerque, New Mexico in January 2011. The team had previously successfully completed a number of other design reviews (SRR, CDR, and PQR) and completed most of the design and integration of both spacecraft. Much of the flight hardware was assembled and operationally tested. The team size was maintained at about thirty, with students from many majors including aerospace, mechanical, electrical, computer engineering and computer science and mathematics. The team and their spacecraft were well-received at the FCR design review, and won the Best Outreach award. The team was accepted to the Nanosat 7 competition, and is now focusing on modifying their Nanosat 6 spacecraft to be more relevant to DoD needs for the Nanosat 7 competition.

15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Henry Pernicka
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified			**19b. TELEPHONE NUMBER** *(include area code)* (573) 341-6749

To: **technicalreports@afosr.af.mil**

Subject: **Final Performance Report to Dr. Kent Miller**

Contract/Grant Title: **Design, Integration, and Flight Test of a Pair of Autonomous Spacecraft Flying in Formation**

Contract/Grant #: **Grant FA9550-09-1-0171**

Reporting Period: **1 March 1 2009– 31 May 2011**

Submitted by: **Henry J. Pernicka, Associate Professor of Aerospace Engineering, Missouri University of Science and Technology**

Date**: July 4, 2011**

1 Final Performance Report

1.1 Document Overview

The purpose of this report is to present the progress made by M-SAT satellite project during the course of its AFOSR grant. This document contains an overview of the mission along with current requirements and constraints. Also included are summaries of each of the following subsystems:

- Structure
- ADAC
- Orbit
- Propulsion
- C&DH
- Power
- Communication
- Thermal
- GSE
- Ground Station
- Documentation
- Testing
- Outreach
- Integration

Subsequent documents, available by request to the PI, focus on the current status of each subsystem in detail. Each document includes discussion of the following topics when relevant:

- Mission Constraints
- Summary of Relevant Literature
- Design and Analysis
- Construction and Assembly
- Testing
- Operations
- Conclusions & Current Status
- References

1.2 M-SAT Overview

The Space Systems Engineering Team at the Missouri University of Science and Technology (Missouri S&T), in conjunction with a number of NASA/industry mentors, is working toward the design, construction, and launch of its first satellite, M-SAT (Missouri S&T Satellite). M-SAT consists of two microsatellites, named MR SAT (Missouri–Rolla Satellite) and MRS SAT (Missouri–Rolla Second Satellite), which will fly in close formation. The goals of M-SAT are to test new technologies for Distributed Space Systems missions, including the study of a R-134a based cold gas propulsion system for formation flying applications and the development of a low-cost wireless communication link between the satellite pair. Data obtained during the close formation flight phase will be evaluated for the benefit of future missions. As a consequence of the modest budget that accompanies a university level project, M-SAT also required the use of innovative, low-cost solutions to meet the stated objectives.

The M-SAT team was accepted into the Nanosat 6 student competition in 2009. This competition is sponsored by the Air Force, and the team's spacecraft was required to be completed by the relatively short deadline of January 2011 for the competition with ten other universities.

The design and construction of M-SAT is a valuable educational experience for the student team. The project provides the experience of using a team approach to solving a real-world assignment and facilitates a fundamental understanding of the spacecraft design process. The approach used in conducting this project is to emulate industry as closely as possible. In this approach students will gain an understanding of engineering ethics along with significant experience in written and oral communication. Appendix A includes an organizational chart showing the current team structure.

1.3 Mission Requirements and Constraints

Mission requirements and constraints were defined for M-SAT, assuming that it would be launched from the Space Shuttle. Although the Space Shuttle will not be used to launch M-SAT, this assumption ensures that the requirements are applicable to a variety of launch vehicles due to the Space Shuttle's demanding constraints. The current mission constraints are shown below in Table 1.1.

Table 1.1 M-SAT Mission Constraints

System	Description	Requirements

		Minimum	Goal	Achieved
Orbit	Altitude (km) Eccentricity Inclination	190 Approx. zero 39^{o}	700 zero 56^{o} or higher	Determined by launch vehicle
Operational Life	Total time in orbit	2 weeks	2 years	TBD
Structure	Shape Length (cm) Width (cm) Diameter (cm) Height (cm) Mass (kg)	Rectangular Prism 50 50 ≤ 50 ≤ 60 ≤ 50	To meet the minimum requirements for the NS6 program.	Hexagonal Prism N/A N/A 48 cm 58 cm 39.13 kg
Communication	Satellite to ground Satellite to satellite	Data rate adequate for telemetry Custom inter-satellite comm. system	Multifunctional RF transceiver Radio using Bluetooth technology	Purchased receiver and transmitter. Bluetooth hardware purchased
Power	Provide electrical power throughout mission	One orbit Primary batteries	Longer mission: Solar cells and batteries with power regulation	Solar panel design with batteries and power regulation board
Propulsion	Cold Gas Thruster	Safe propulsion meeting requirements for the launch vehicle	Full orbital and secondary attitude control of MR SAT	Propulsion system designed for MR SAT orbital and attitude control.

<table>
<tr><td>ADAC</td><td>Determine attitude and control passively if possible</td><td colspan="2">Control of both satellites to within ±5.0°</td><td colspan="2">Control of both satellites to within ±1.0°</td><td colspan="2">Control of both satellites to within ±5.0°</td></tr>
<tr><td>Telemetry, Tracking, and Control</td><td>Navigate spacecraft and return science and engineering data</td><td colspan="2">Control from Ground Station located at MS&T</td><td colspan="2">Control from Ground Station located at MS&T and other ground stations</td><td colspan="2">Ground Station Hardware located and design finalized</td></tr>
<tr><td>Thermal</td><td>Thermal control of spacecraft</td><td colspan="2">Maintain acceptable thermal limits for payload and satellite</td><td colspan="2">Passive control of thermal limits for payloads and satellite</td><td colspan="2">Thermal sensors installed on key components</td></tr>
<tr><td>Payload and Key Technologies</td><td>Payloads providing scientific and/or engineering data</td><td colspan="2">Autonomous control and relative navigation system</td><td colspan="2">Autonomous control, rel. nav. and wireless communication between spacecraft</td><td colspan="2">High fidelity model of autonomous guidance, navigation, and control.

Wireless comm. functional</td></tr>
<tr><td>Launch Vehicle</td><td>Any means by which to place spacecraft into low Earth orbit</td><td colspan="2">Any launch opportunity into low Earth orbit</td><td colspan="2">Adaptable to any launch vehicle as secondary payload</td><td colspan="2">Lightband integration ready</td></tr>
<tr><td>Launch Vehicle Adaptor</td><td>Method of attaching spacecraft to launch vehicle</td><td colspan="2">To be developed to fit launch vehicle safety requirements</td><td colspan="2">Developed to fit or be easily adapted to the launch vehicles</td><td colspan="2">Developed to fit or be easily adapted to the launch vehicles</td></tr>
<tr><td>Command and Data</td><td></td><td>MR SAT</td><td>MRS SAT</td><td>MR SAT</td><td>MRS SAT</td><td>MR SAT</td><td>MRS SAT</td></tr>
</table>

Handling	Power (W):	5	5	< 3	< 3	< 2	< 2
	Memory (MB):	4	4	64	64	64 SDRAM 32 MB StrataFlash 1 MB ROM 1 CF Slot	64 SDRAM 32 MB StrataFlash 1 MB ROM 1 CF Slot
	CPU:	No Processor, 4 x 8051 Micro Controllers	No Processor, 1 x 8051 Micro Controllers	386.25 MHz +, 5 x 8051 Micro Controllers	No Processor, 1 x 8051 Micro Controller	ARM 400 MHz, 5 x 8051 Micro Controllers	1 x 8051 Micro Controllers
	Dimensions (cm):	25 x 20 x 3	25 x 20 x 3	8 x 6 x 2	8 x 6 x 2	9.65 x 9.14	9.65 x 9.14
	Mass (kg):	0.5	0.5	< 0.5	< 0.5	0.5	0.5

1.4 Project Status

The following sections include a brief description of the M-SAT team infrastructure and a summary of each subsystem and its current status. A more thorough discussion of each subsystem may be found in respective design documentation. These documents are available from the M-SAT website at www.mst.edu/~mrsat.

1.4.1 Basic Infrastructure

1.4.1.1 Systems Engineering

The M-SAT project utilizes a Chief Engineer/Program Manager approach to project management. At the highest level of project management is the Project Director, Dr. Henry Pernicka. Under the Project Director is the Chief Engineer, whose primary task is to fully integrate the efforts of the entire team from an engineering design standpoint, and a Program Manager, whose task is to keep the team organized and efficient. The Program Manager runs a weekly team meeting in which each subsystem leader briefs the team on their progress and any issues they may be facing. Prior to the weekly team meeting, each subsystem is required to meet with the Project Director, Chief Engineer, and Program Manager to discuss the progress of the subsystem. All members of the subsystem are required to attend, and these meetings allow more direct management of subsystem and team issues than the weekly team meeting alone. The Chief Engineer and Program Manager work together to establish team goals and milestones, while assigning tasks to ensure that these objectives are met in an efficient and timely manner.

The Chief Engineer and Program Manager act collectively as a team leader. A significant responsibility of the team leadership is to ensure that the team maintains a spirit of teamwork, high morale, professionalism, and high ethical standards. They are also in charge of establishing standards of communication, documentation, and presentation, as well as organizing design reviews and design documents.

A cadre of industry mentors also provides guidance to the project. These industry professionals provide input and technical assistance to the subsystems. Their review of the spacecraft design is a valuable contribution to M-SAT and ensures that a viable spacecraft can be realized. The current group of mentors includes representatives from the Air Force Research Laboratory, NASA's Goddard Space Flight Center, the Jet Propulsion Laboratory, Boeing, Lockheed Martin, as well as other companies.

1.4.1.2 Space Systems Engineering Lab

The Space Systems Engineering (SSE) Lab at MS&T is a facility dedicated to the M-SAT project as well as other space-related research and education. The lab is equipped with PC workstations, a clean room, workbenches, ESD safe workbenches, and tools. The five workstations are equipped with software that provide programming capability, computer-aided-design, structural and thermal analysis, and systems engineering software.

The SSE lab is also equipped with a 6' x 6' x 8' clean room rated and tested as Class 1. This clean room consists of a 6-36 vertical flow hood supported by two 3' x 6' x 8' frame members and is enclosed by vinyl strip curtains. The clean room was used for final assembly and storage of the spacecraft. Included in the SSE lab are two 5' x 2.5' workbenches and tools (drill, dremel tool, multimeter, torque wrenches, etc) to use in spacecraft construction. Both the clean room and the workbenches are equipped with ESD wrist straps and grounding mats for use with flight hardware. An industrial grade oven has been installed in the lab for use in component bake-out. A fully equipped machine shop, CNC, Rapid Prototyping, and waterjet facilities are also readily available on campus as needed for assistance in the component manufacturing process.

1.4.1.3 M-SAT Web Site

The role of the website in the M-SAT project is to display current events with the project throughout each semester. The primary function of the website is to keep mentors and contacts updated on the progress of each subsystem. The web page of each subsystem includes an overview of their responsibilities, semester goals, semester meeting times and location, and monthly updates on their progress. The website also includes a summary of the overall mission of the project, team biographies, and pictures of satellite hardware and testing. The M-SAT website may be accessed at www.mst.edu/~mrsat.

1.4.2 Subsystem Summary

1.4.2.1 Structures

The Structures subsystem is responsible for the load-bearing body of the spacecraft. A sturdy structural design with sufficient capacity to carry all necessary components is essential to a spacecraft’s mission success. It is also essential to limit the mass and size of the spacecraft in order to lower the costs associated with placing it in orbit. These primary constraints drive the overall structural design of most spacecraft. In January of 2009, the M-SAT design team was accepted into the University Nanosat 6 Competition. The constraints and requirements of this competition play a large role in the structural design.

A number of constraints were developed for the execution of this project. These constraints include limiting total mass to less than 50 kg, and total size to dimensions within a cylindrical envelope of 60 cm diameter and 60 cm high. Additional mission goals include designing the two satellites to be mated during launch and to separate on orbit. The basic concept for the satellite structure (in mated formation) is shown below in Figure 1.1.

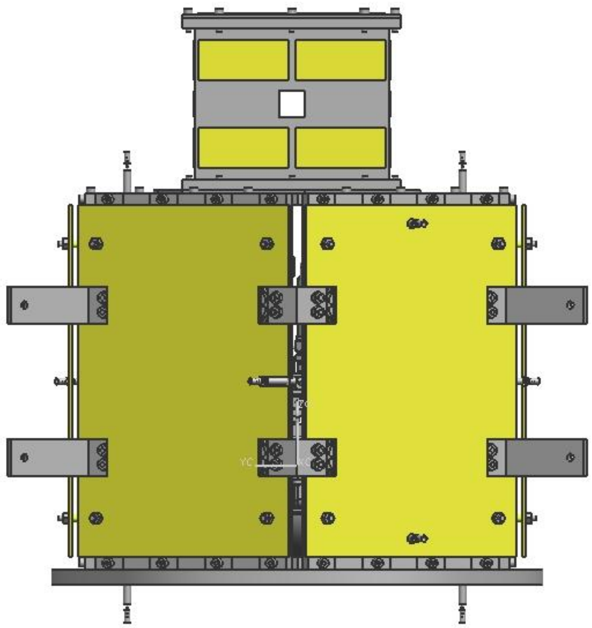
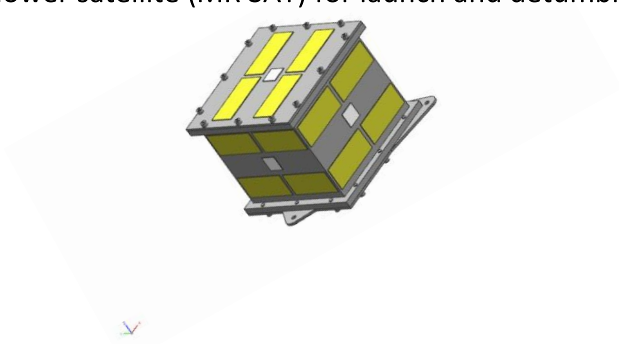


Fig. 1.1 Structural Concept for MR SAT & MRS SAT

The structure of each satellite was to be a hexagonal prism, although MRS SAT was modified to a near-cubical shape as its design was refined and simplified. MR SAT is the larger of the two satellites and is shown on the bottom of Figure 1.2 with the upper satellite being MRS SAT. Figure 1.2 shows the two satellites separated as they will be during the initiation of the formation flight sequence of the mission. The upper satellite (MRS SAT) will be hard-mounted to the lower satellite (MR SAT) for launch and detumble.



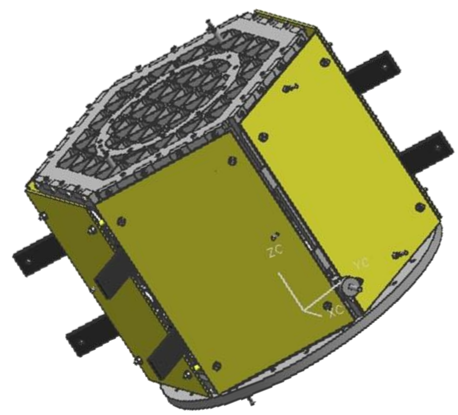


Fig. 1.2 Structural Concept for MR SAT & MRS SAT After Separation

The largest and highest power consuming components were placed in MR SAT where there is more available space for solar cells (seen in yellow in Figure 1.1 and 1.2). These components are notably the propulsion tank and the orbit to ground communication.

The structural design incorporated the requirement for ground support equipment with the metal brackets that can be seen extending out of four of the corners of the two satellites. The mounting of the satellite to the launch vehicle can be seen in the round base plate on the bottom of MR SAT. This ¼ inch plate will be connected to the launch vehicle using 24 bolted connections rigidly attaching the satellite to the Lightband system.

In designing the internal configuration, all component boxes will be mounted to the six side panels. The tank is attached to the bottom of the satellite and has tubing running throughout MR SAT. Four antennas are mounted to the honeycomb panels on MR SAT. MRS SAT's design is a cube shaped box with solar cells and patch antennas fitted to each side. The docking mechanism between MR SAT and MRS SAT is a NEA quick release bolt system. This will hold the two satellites together until the computer autonomously sends a signal to the three NEA devices and releases the satellites. In order to meet mission requirements, the mass and size of the satellite must be minimized while strength and stiffness are maximized. The mass of the satellite was maintained at a manageable level due to the lightweight materials used (aluminum isogrid panels, boxes, etc). The relatively small dimensions used also leads to high stiffness.

It is also the responsibility of the Structure subsystem to verify that the structure can withstand all loads that may be applied to it over its lifespan. For this reason a number of analyses including finite element, vibration effects, and thermal expansion effects were performed.

Preliminary analyses were conducted initially for concept generation. This was followed by in-depth studies to determine if the detailed design will survive the loading and environmental conditions during launch. The various analyses completed include:

- Finite Element Analysis
- Mass Properties Analysis (masses, centroids, moments of inertia)
- Vibration Effects Analysis

All analyses showed the design to be within required safety margins. Mass properties of the satellite were revised after acquiring a better understanding of how the software computed the values. A vibration effects analysis was completed, resulting in two master's theses.

Testing will also be necessary to verify the results of these analyses. Before completion of the project, the spacecraft will undergo a series of tests to insure the structural integrity within the design limits and verify the results of the analyses in Section 3.4.3. Potential testing facilities have been researched, and arrangements are currently underway to perform the required testing. Once the spacecraft has been assembled it will be tested and subjected to all the loads it is expected to undergo throughout its operational life, with particular focus on its ascent to orbit.

1.4.2.2 ADAC

The responsibilities of the ADAC subsystem include the tasks of determining the orientation of the spacecraft and maintaining a desired orientation to facilitate completion of the mission objectives. Attitude, or the orientation of a spacecraft, is crucial to the success of a mission. Improper determination or control of the attitude of the spacecraft can lead to catastrophic results. For example, solar cells on a spacecraft must be oriented towards the Sun; failure to maintain specific orientations would lead to rapid depletion of the batteries. There are also potentially damaging thermal effects as well as loss of communications that can arise from incorrect attitude of the spacecraft.

Maintaining proper orientation of the spacecraft will not only protect against mission failure, but it will also ensure a maximum operational life of the spacecraft. The amount of time that the spacecraft will be in range of communication with the ground station will partly determine how much data can be transferred to and from the spacecraft. However, precise control of the antennas onboard the spacecraft will facilitate the transfer of more data. The position of the antennas will be controlled by the attitude of the spacecraft, so it will also be the job of the Attitude subsystem to maintain the data rate at a high level.

The mission requirements for the attitude of M-SAT consist of: three-axis control while consistently pointing the space-to-ground antenna towards Earth with an accuracy of plus or minus five degrees, rotate 360° per orbit about the pitch axis, and maximize the slew rate so orbital maneuvers can be efficiently performed during the formationkeeping sequence.

Magnetometers will be the primary components for attitude determination, while magnetic torque coils, with cold gas thrusters as a backup, will be the primary component for attitude control. Research has been conducted on the equations of motion and the closed-loop formationkeeping controller. The attitude determination and control code will incorporate the robust θ-D filter developed at Missouri S&T. The flight hardware has been fabricated on campus or procured from the manufacturer and is undergoing testing at Missouri S&T. The code is nearing completion and simulation results show that all ADAC objectives can be met.

1.4.2.3 Orbit

By making use of the orbital elements, such as the instantaneous position and velocity of a spacecraft, it is possible to predict the satellite's future trajectory. This method is based on the use of a set of equations of motion derived from the dynamics of the satellite. Conventional satellites can normally be accurately modeled using equations derived from the two-body problem, with the Earth and the satellite as the two spherical bodies. The orbits obtained using this two-body method can fall into one of three categories: elliptical, hyperbolic and parabolic (known as "Keplerian orbits"), each with their own characteristics and applications. These equations of motion will be relevant during the free-flying portion of MR SAT and MRS SAT's orbits. The orbit that is applicable to the free-flying portion of M-SAT's operation is that of an elliptical nature, or more precisely a near-circular orbit.

The primary method of determining the orbital elements of the M-SAT spacecraft will be through the use of the Global Positioning System (GPS). A GPS receiver onboard each satellite will be able to collect the position and velocity of each satellite at any given time and store it until it can be downloaded. The data received will include latitude, longitude and altitude, plus velocity magnitude and heading. It is then possible to solve for the orbital elements and determine where the satellite will be in the near future. Adjustments may have to be made to the orbit determination (OD) process to provide an accurate prediction of the orbit to allow for precise control of M-SAT, since the exact orbit of M-SAT is currently unknown. Several factors have to be taken into account before its final orbit can be determined. These factors, such as the launch vehicle obtained, can change the M-SAT mission significantly.

MR SAT will “chase” MRS SAT during flight. To do this, MR SAT will receive the position of MRS SAT obtained from her GPS receiver. Then the Orbit subsystem’s formationkeeping code will calculate a change in velocity that needs to be executed by the propulsion system in order to match the trajectory of MRS SAT.

Currently, the Orbit subsystem has purchased two GPS receivers from Spacequest Ltd. Spacequest is registered with ITAR and has delivered two unrestricted receivers and a restricted terrestrial engineering unit to assist with spacecraft integration and ground testing.

1.4.2.4 Propulsion

The main use of a propulsion system is to provide a means to maneuver a satellite through space. This maneuvering is typically used for changing the orbit shape and size. A secondary use for the propulsion system is to provide a means for attitude control.

Research was conducted to determine the propulsion options available to the M-SAT project leading to the identification of many types of propulsion systems. Most of these were not suitable for the M-SAT project due to size, mass, budget, or power requirements; however, several promising options for propulsion were found. After careful consideration, a cold gas thruster system with two main propellant options, the compressed gas Xenon and the saturated liquid R-134a, was pursued. Given the potential performance advantages of saturated liquid propellants, R-134a was the final propellant selected. Due to design limitations specified by the Nanosat 6 competition, specifically the use of pressure vessels and substances capable of phase changes, the use of R-134a required in-depth analysis and testing prior to it being accepted by AFRL. In the event R-134a was not accepted by AFRL, an alternative backup option utilizing Xenon propellant is documented in this report. As designed, both propellant options can be integrated with the same hardware.

For the design configuration, the length of the tank was located perpendicular to the z-axis of the satellite and orientated with the outlet facing a hexagonal corner. An example of this can be seen in Figure 1.2. It was required that the tank be placed as close as possible to the center of mass (CM) of MR SAT when MRS SAT is undocked. This placement minimized the CM movement effects on attitude determination and control as the propellant is expelled and the MR SAT mass decreases. This exact placement was coordinated with the Structure and Integration subsystems.

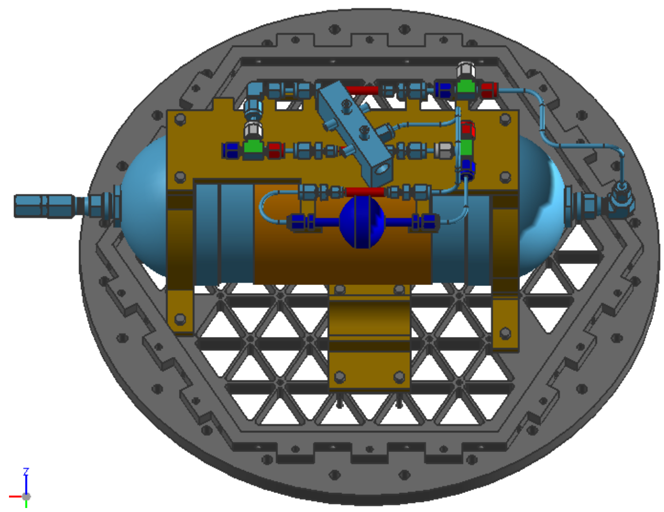


Figure 1.2 Example Propellant Tank Location and Orientation

The operation of the thrusters will be autonomously controlled through the formationkeeping algorithm developed by the ADAC and Orbit subsystems with the ability to command additional firings through a communication uplink.

1.4.2.5 Command and Data Handling

The onboard computer must accomplish several distinct tasks: coordinating subsystems to work together, storing and processing data from onboard sensors, running the spacecraft-to-Earth communications system, and running the communications system between both satellites. The following summarizes the selection process for both hardware and software components to be used onboard the satellites.

Low Earth orbit (LEO) satellites experience radiation bombardment as well as intermittent high level bursts of radiation not regularly experienced here on Earth. This radiation can interfere with or even permanently damage electronic equipment. This requires that all electronic equipment be shielded to some degree to ensure error-free operation. Due to size and mass constraints, shielding may often be less than desired. Therefore, electronics systems, more specifically the onboard computer, microcontrollers, and radio equipment must be able to cope with and protect against the effects of radiation. Radiation has two distinct effects on the electronic systems. The more catastrophic of the two is failure of an electronic component or even the entire system. This severity of failure is uncommon in LEO and, therefore, protection is focused on the second effect. This second, less severe, type of interference can manifest itself in the form of single event upsets (SEU) or single event latch-ups (SEL). Radiation bursts can cause a reversal of a bit or even sections of data within the processor, memory, or bus. Radiation hardened processors, which can detect and correct these errors, can be used in space applications; however, these are typically out of the price range of university design teams.

Power usage is a concern for any satellite and an onboard computer potentially can be a large user of that energy. Due to the size of MR SAT and MRS SAT, there is limited space available for solar cells and since each subsystem must share, power usage by each piece of hardware must be minimized.

The workload of the onboard computer is divided into high-level and low-level classes. The low-level processing is concerned with controlling the closed-loop type processes associated with each subsystem. Devices are connected via a 1-wire data bus which relay the relevant information to a central processor that is responsible for central data storage, system maintenance, and any relatively intense computations which may be necessary including interfacing with the GPS unit, running orbit and attitude determination algorithms, and all input or output with the memory. The central processor is also be responsible for operating both the MR SAT to ground and MR SAT to MRS SAT communication equipment. The data bus interfaces with the hardware of certain subsystems which require constant attention and provides an easier interface for the processor to control those subsystems.

The software onboard MR SAT and MRS SAT is responsible for controlling communication devices, subsystem data collection, power regulation, and basic automation commands.

1.4.2.6 Power

The objectives of the power system are to acquire, store, and distribute power in a way that will sustain the operations of the mission. In order to achieve these objectives, a satellite power system must consist of the following components: a power generation system, an energy storage system, a power distribution system, and a power regulation system. For the M-SAT spacecraft, the power generation system consists of solar cells and the energy storage system consists of secondary batteries. Each of the major components of the electrical power system is discussed in further detail in a following section.

The two satellites, MR SAT and MRS SAT, are hexagonal in shape with solar panels placed on all six sides of the satellites with an additional solar panel on the top of MRS SAT. The size of each panel varies based on thruster and antenna placement. The amount of power produced by the solar panels depends on several different parameters including the cell voltage, cell current, Sun incident angle, temperature and ratio of the Sun power density in space and on Earth. Secondary batteries are used to supply power while the satellites are in the Earth's shadow.

In the current design of the solar arrays, cells are mounted on honeycomb panels that are attached to the body of the satellite using short stand offs. To provide a steady source of power for the mission operations while in Earth's shadow, the satellite is equipped with a bank of secondary batteries. Acting as a power reservoir, these batteries will be recharged and must be capable of providing power during the eclipse phases of the mission, as well as during periods when the satellite power draw exceeds the power generated by the solar panels.

To lengthen the life of the batteries and enhance the function of the satellite, the power distribution electronics is designed for maximum flexibility. This flexibility will help prevent critical failure of the mission if any problems arise. The solar panels and batteries are wired in parallel. The incoming energy from the solar panels charge the batteries and power any operating devices on the satellite. The batteries are used to supplement the solar arrays in peak load situations, as well as provide power to the satellite during eclipse. Furthermore, the satellite can operate solely upon the solar arrays, although functions would be limited to sunlit portions of the orbit only.

The power distribution and regulation systems provide and route power to each device on the satellite. These two systems will convert battery bus voltage to the voltages appropriate for each device, protect the satellite from shorts and surges, and act as the hardware component for the power regulation duties of the onboard computer.

1.4.2.7 Communication

The communication system is necessary to relay information from the ground station to MR SAT and from MR SAT to MRS SAT. The communication link between the ground station and MR SAT is used to transmit commands and receive data collected in space. Because the M-SAT project is composed of two separate spacecraft, a second communication link is required to connect the pair.

The space-to-ground communication system onboard MR SAT is composed of a transmitter, a receiver, and two antennas. In order to reduce the complexity of the entire system, different antennas are used for reception and transmission. The entire space-to-ground communication system uses downlink frequencies in the UHF Band (430-460 MHz) and uplink frequencies in the VHF Band (140-150 MHz).

The intersatellite communication system is based on commercial off-the-shelf, low-cost wireless technologies. Selected transmitters and receivers rely on Bluetooth technology and commercial non-space-rated equipment has been selected and acquired. In order to protect these products, they have been upgraded with radiation shielding; however, antennas will need to endure the harsh space environment (vacuum and very high temperature gradients). Thus, special purpose space-rated antennas were built.

The space-to-ground communication components have been selected. The UHF downlink will be performed by the Spacequest TX-435 transmitter interfacing with a GMSK modem manufactured by the Command and Data Handling subsystem using the CML Microcircuits CMX589A modem chip. The TX-435 transmits all telemetry and data signals via a Times Microwave M17/60 (RG-142) coaxial cable to a half wavelength dipole antenna mounted near the surface of MR SAT. VHF uplink signals are received by a Spacequest RX-145 VHF receiver via a Spacequest quarter wavelength monopole antenna and the RG-142 cable. All uplink signals are relayed to the same modem and processed to the spacecraft computer. The intersatellite communication system was originally designed using two WiSER2400 transceiver prototypes which were purchased and tested. This system was redesigned to incorporate Bluetooth technology. Bluegiga's WT-11E will be flown in pairs on both spacecraft (a total of four units). This will allow each unit to have its own dedicated antenna and function in a piconet. This allows either or both spacecraft to maintain virtually any orientation relative to each other.

The testing process has just started for Bluetooth technology and its evolution will be closely related to the onboard computer software implementation. The next step is prepare an intense testing process of the global package (onboard computer and wireless communication devices) to verify the robustness of the system.

1.4.2.8 Thermal

The goal of the Thermal subsystem is to implement hybrid control of the thermal limits for both satellites and their payloads. The satellite equilibrium temperature is governed by radiation and internal heat dissipation. Convection is not considered for the satellites due to the vacuum (or near vacuum) environment in which they operate. The temperature can be controlled, within limits, by using heat sinks, insulation, anodized aluminum and coatings. By connecting the components of the satellite using conduction pathways, a nearly uniform temperature can be maintained within both satellites. Conduction from the element depends on the heat transfer coefficient of the material and contact pressure, and can be used to effectively transfer heat throughout each satellite.

The objectives of the Thermal subsystem are to analyze the satellite thermally, determine the safe working temperature range for the orbit specified, and to utilize methods that will ensure the thermal safety of the satellites over large temperature ranges. Temperature measuring sensors were installed, tested and integrated into both satellites.

A finite element analysis program, NX4, was used to analyze the conduction and radiation of the satellites to estimate worst-case equilibrium temperature. Convection can be ignored in space; unless pressured modules or fluid loops are used since convection is transfer of heat through a fluid (molecules in space are too sparse to transfer significant heat). Nodes for the thermal analysis are governed by type and size of mesh applied for the analysis. After the completion of the steady-state thermal analysis, a transient-state analysis is was conducted to enhance accuracy of the results obtained from the steady-state analysis.

The design strategy is to concentrate on minimizing the effects of thermal deformations and stresses. This includes enclosing critical members in insulation to keep temperature gradients low, accounting for friction in sliding joints, using structural members with low coefficients of thermal expansion (CTE), designing joints that connect members of different materials, using materials with high thermal conductivity, and determining how temperature affects the strength of composite materials. A catalog of the thermal properties of each material used on the satellites was made. Batteries have a very small operating range which makes them the most critical component for thermal control. Hence, the batteries govern the allowable ranges for satellite temperature variation.

The effects of the beta angle are being determined by analyzing orbits at different altitudes and orientation and studying differences in total heat or irradiation due to different sources such as the Sun, Earth, and albedo. Numerous thermal control methods were studied for possible applications to the project. These included the use of conductive links to short all the parts of the satellite, black paints on the electronic boxes, FOSR radiators, conductive pastes, insulation, cooling system, and instruments that switch on when the satellite becomes too hot or too cold. Temperature sensors are required for the batteries, solar panels, camera, and CPU. Maxim/Dallas Semiconductor DS18B20 digital temperature sensors have been chosen for M-SAT.

Electronic components were tested for functionality through low pressure and over a wide range of temperatures in an effort to identify any faulty hardware. Thermal barrier materials were tested to determine what and how much is being used in the final design. The thermal sensing equipment requires calibration to ensure accurate readings. The final design will also be subjected to ground test in the thermal environment it is expected to endure on orbit. Effects of spin rate and orbital decay on the temperature of the satellite are being analyzed.

The responsibilities of the Thermal subsystem during operation include temperature monitoring and control. Temperature sensors will read the temperature variations of vital components while the satellite is in orbit. The onboard computer is able to analyze the data to insure the satellite remains in its safe ranges and stores and sends data to the ground station for further analysis.

1.4.2.9 Ground Support Equipment

The responsibilities of the Ground Support Equipment (GSE) subsystem were focused on the successful mating of M-SAT with the Lightband separation system, development of the EGSE (Electrical GSE) equipment, and MGSE (Mechanical GSE). The mechanical and electrical interfaces must be designed such that the satellite can survive the severe vibro-acoustic and shock environment associated with launch operations. The subsystem must ensure that the satellite can be handled by ground support equipment and facilities in preparation for final mating before launch. The satellite itself must be able to be handled by support equipment at Missouri S&T, AFRL, and anywhere else that might be required.

With acceptance to the Nanosat 6 competition, extensive research was conducted by the GSE subsystem. An extensive list of current launch vehicles was compiled, along with contact information for each respective company. The GSE subsystem also researched candidate launch vehicle adaptors. Most launch vehicles provide their own adaptors; however, in the event that the final launch vehicle does not provide an adaptor, extensive research is being conducted on the Lightband Separation System.

The GSE subsystem is considered the safety concerns in the general sense of the overall satellite: to ensure it will be safe to fly as a secondary payload. Safety is very important especially when testing some of the new technologies that the team researched itself. Now that extensive component and subsystem testing is underway and the prototype testing has started, safety to M-SAT and the team members is of the highest priority.

Mission constraints applicable to the GSE subsystem state that the satellite must be able to mate with the Lightband Separation System. The exact format of the mating plane was heavily dependent on the structure of M-SAT. Selection of the hexagonal shape of the satellite meant that the satellite footprint would not sufficiently cover the Lightband ring such that all mating bolts could be utilized; thus, an adapter ring was designed so that the 24 Lightband bolts could all be used to mate the satellite to the separation ring.

Ground testing is done to validate satellite operations through use of the EGSE cart. Equipment on this cart is able to indicate the power stored powering each battery cell for both satellites.

The electrical constraints are derived primarily from the Nanosat User's Guide, Section 6.2.3, and the specifications of the Lightband ring itself. Two or four 15-pin electrical connectors will be used in conjunction with two or four separation microswitches to relay all relevant telemetry data to ground crews during launch.

Additionally, the User's Guide requires a system to support ground handling operations both at the university level and at the launch vehicle integration site. A system was developed to lift the satellite vertically, and if necessary, rotate it 90 degrees to a horizontal position and continue to carry it in that position until mated with the launch vehicle.

For integration purposes, platform stands will secure work places for satellite construction. Each piece of equipment has been designed for a safety factor an ultimate strength safety factor of 5 as required by the Nanosat User's Guide, Section 6.3.3.4. The crane used to carry the assembled satellites will lift from a sing point above the center of gravity and is controlled by an electric winch. During transportation, each satellite will be wrapped in an electro static discharge blanket and will be housed in crates provided by the GSE subsystem.

1.4.2.10 Ground Station

The goal of the Ground Station subsystem is to develop and integrate ground station equipment into the MR SAT system. Essentially, it is the earthbound leg of satellite operations, conducted primarily through the Communications and Command and Data Handling subsystems. Communication with MR SAT is essential to the success of the mission. It is for this reason that a ground station must be established at Missouri S&T.

On Earth, amateur radio equipment run by M-SAT members and the Missouri S&T Amateur Radio Club will be utilized for communication from the campus ground station to MR SAT. MR SAT will have to relay any command towards intended for MRS SAT. The ground station must have several components in order to properly perform its duties, namely telemetry, tracking, and control (TT&C).

The Ground Station will be located in the new Space Systems Engineering (SSE) Laboratory located in Toomey Hall. The radio communications will be transmitted and received via two Star Antenna quad-stacked Yagi-Uda antennas tuned to VHF and UHF band frequencies. These antennas will be located on the roof of Toomey Hall. The Icom IC-910H satellite radio transceiver will process all radio signals to and from the Kantronics KPC-9612+ terminal node controller (TNC). This TNC operates around the same GMSK form of modulation that the CMX589A chip on MR SAT utilizes. The control source for ground operations will be a desktop computer controlling the data being sent via the TNC and transceiver, as well as tracking the antennas via the Yaesu G-5500 antenna rotors.

1.4.2.11 Documentation

The goal of the Documentation System is to establish a Configuration Management process which successfully organizes and correlates all documents from each subsystem. To achieve this goal, a process for creating, cataloging, storing and updating documents was established. Every document created for use by anyone on the M-SAT team will have four pages to precede each document, consisting of a title page, a revision summary page, a document author signature page and a table of contents. From this point forward the individual creating the document has the freedom to compose text in most any professional format they deem necessary. However, they must have page numbers listed on all pages; excluding the title page. These documents are also being transferred to a Wiki Concurrent Versioning (CVS) system which allows team members to update any document from any location with Internet access. This system will track all changes to any document and save all previous versions of that document. It will also track multiple versions of images and formulas associated with each document.

1.4.2.12 Testing

The Testing subsystem oversees all of the testing plans as well as actual testing at the component level, subsystem level, and system level. This includes the prototype testing as well as the flight model testing. When a test is conducted, a testing log sheet is completed with details about that test. The Testing subsystem then takes the testing logs and compiles them into an overall testing log. Types of testing include vibration, thermal, electromagnetic, acoustic, radiation, vacuum, and various other component specific tests.

1.4.2.13 Outreach

The goal of the Outreach subsystem is to promote the field of Astronautics to students of all grade levels and to inform the public about the efforts and accomplishments of the M-SAT team and the University Nanosat Program.

Development of the Outreach program has been accomplished by teaming with the Missouri S&T Miners in Space team as well as the University's outreach programs. Not only does the team desire to inspire future engineers, but also to interact with them. Efforts are being made to provide meaningful cooperation with high school level education programs to have student interaction with either their programs or the M-SAT team project. A prime example of this is the CASA program (http://teachers.columbia.k12.mo.us/hhs/fthompso/casa/) at Hickman HS in Columbia, Missouri, in which Missouri S&T students work with teachers and students to simulate a week-long space mission.

Program development also continued in the following areas:

1. Continuing development of educational presentations to all grade levels

2. Finding and creating more programs at the high school level in surrounding communities

3. Developing a program that allows high school students to be involved in the M-SAT Design Team

1.4.2.14 Integration

The Integration subsystem was created to manage the final integration of all hardware into the flight satellites. This subsystem is responsible for producing and compiling all of the assembly procedures for the various subsystem components and component boxes, as well as the final spacecraft. This effort culminated in the final integration of the spacecraft presented at AFLR's FCR in January 2011.

1.5 Conclusion

As participants in AFRL's University Nanosat Program, the Missouri University of Science and Technology successfully produced a nearly flight-ready microsatellite that was presented at the Final Competition Review held in Albuquerque, New Mexico in January 2011. The team had previously successfully completed a number of other design reviews (SRR, CDR, and PQR) and completed most of the design and integration of both spacecraft. Much of the flight hardware was assembled and operationally tested. The team size was maintained at about thirty, with students from many majors including aerospace, mechanical, electrical, computer engineering and computer science and mathematics. The team and their spacecraft were well-received at the FCR design review, and won the Best Outreach award. The team was accepted to the Nanosat 7 competition, and is now focusing on modifying their Nanosat 6 spacecraft to be more relevant to DoD needs for the Nanosat 7 competition.

The successful design, production, and launch of M-SAT will be of great value to the Missouri University of Science and Technology and the aerospace community. Missouri S&T students are benefiting from the hands-on experience of designing and building a satellite, while the aerospace community will benefit from the engineering and scientific return obtained at a modest cost. Further information regarding M-SAT can be obtained by contacting the Project Director, Dr. Henry Pernicka, at (573) 341-6749 or pernicka@mst.edu.

1.6 List of M.S. Theses as a Product of this Grant

1 Sanders, Tonya. Shaker Table Vibration Testing of a Microsatellite, M.S. thesis, Missouri University of Science and Technology, 2011.

2 Searcy, Jason. Magnetometer-Only Attitude Determination with Application to the M-SAT Mission, M.S. thesis, Missouri University of Science and Technology, 2011.

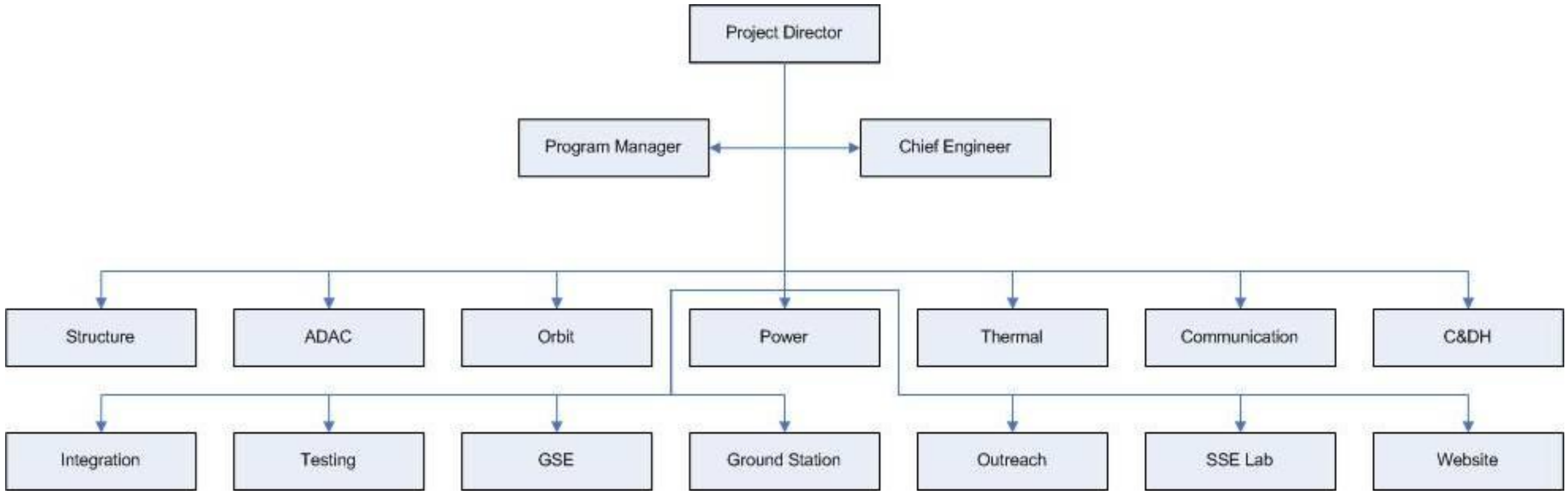
3 Pahl, Ryan. Integration and Test of a Refrigerant-Based Cold Gas Propulsions System for Small satellites, M.S. thesis, Missouri University of Science and Technology, 2010.

4 Dancer, Michael. Analysis of the Theta-D Filter as Applied to Hit-to-Kill Interceptors and Satellite Orbit Determination, M.S. thesis, Missouri University of Science and Technology, 2010.

5 Miller, Shawn. Management of a University Satellite Program with Focus on a Refrigerant-Based Propulsion System, M.S. thesis, Missouri University of Science and Technology, 2010.

6 Siebert, Joseph. Design, Hazard Analysis, and System Level Testing of a University Propulsion System, M.S. thesis, Missouri University of Science and Technology, 2009.

Appendix A: M-SAT Organizational Chart



Project Director
Program Manager
Chief Engineer
Structure
ADAC
Orbit
Power
Thermal
Communication
C&DH
Integration
Testing
GSE
Ground Station
Outreach
SSE Lab
Website